

NUCLEOSYNTHESIS INSIDE GAMMA-RAY BURST ACCRETION DISKS

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We investigate nucleosynthesis inside both a gamma-ray burst accretion disk and a wind launched from an inner region of the disk using one-dimensional models of the disk and wind and a nuclear reaction network. Far from a central black hole, the composition of accreting gas is taken to be that of an O-rich layer of a massive star before core collapse. We find that the disk consists of five layers characterized by dominant elements: ^{16}O , ^{28}Si , ^{54}Fe (and ^{56}Ni), ^4He , and nucleons, and the individual layers shift inward with keeping the overall profiles of compositions as the accretion rate decreases. ^{56}Ni are abundantly ejected through the wind from the inner region of the disk with the electron fraction $\simeq 0.5$. In addition to iron group, elements heavier than Cu, in particular ^{63}Cu and ^{64}Zn , are massively produced through the wind. Various neutron-rich nuclei can be also produced in the wind from neutron-rich regions of the disk, though the estimated yields have large uncertainties.

1. Introduction

Observational evidences have been accumulated for a connection between gamma-ray bursts (GRBs) and supernovae (SNe): association of SN 1998bw and GRB 980425¹ and SN 2003dh in afterglow of GRB 030329.² A *collapsar* model is one of promising scenarios to explain a huge gamma-ray production in GRBs and GRB/SN connections.^{3,4} During collapse of massive stars, stellar material greater than several solar masses falls back on a new-born black hole with extremely high accretion rates ($\leq 1M_{\odot} \text{ s}^{-1}$).⁵

An accretion disk forms around the hole due to the angular momentum of the fallback material.^{3,4,6} In the context of the collapsar model, jet-like explosion driven by neutrino annihilation and nucleosynthesis in the jet has been investigated.⁷ Although ^{56}Ni with high velocity ($> 0.1c$) can be massively produced, it is not sufficient for an observed amount in SN 1998bw.⁷ In addition to the production via the jet, massive synthesis of ^{56}Ni is also suggested in winds launched from the accretion disk.^{3,8} Neutron-rich nuclei may be produced through r-process inside the wind ejected from an inner, neutron-rich region of the disk.⁸ In the present paper, we examine nucleosynthesis inside a GRB accretion disk and investigate abundance change through the wind launched from the disk.

2. Disk Model and Input Physics

We construct a steady, axisymmetric model^{9,10} of the disk around a black hole of mass M with accretion rates up to $10M_{\odot} \text{ s}^{-1}$. The black hole mass is fixed to be $3 M_{\odot}$ and the viscosity parameter is set to be $\alpha_{\text{vis}} = 0.1$. Figure 1 shows the profiles of density, ρ , (thick lines) and temperature, T , (thin lines) in the accretion disk for $\dot{M} = 1$ (solid lines), 0.1 (dotted lines), and $0.01M_{\odot} \text{ s}^{-1}$ (dashed lines). These profiles are roughly agreement with the corresponding profiles in another disk model⁹ except for the region near the disk inner edge; our density and temperature drop rapidly near the inner edge. This is attributed to our use of the pseudo-Newtonian potential and the zero torque condition at the inner edge.

Chemical composition of accreting gas far from the black hole is set to be that of an O-rich layer of a $20 M_{\odot}$ star before core collapse.¹¹ Once temperatures and densities are evaluated inside the disk, using a nuclear reaction network,^{12,13} which includes 463 nuclei up to ^{94}Kr , we follow evolution of the composition in the accreting material during the infall onto the hole. We note that at the inner region of the disk, where $T \geq 9 \times 10^9 \text{ K}$, the composition is in nuclear statistical equilibrium (NSE).¹⁴

3. Abundance Distribution inside Disks

Figure 2 shows the abundance profiles of representative nuclei inside the disk with $\dot{M} = 0.1M_{\odot} \text{ s}^{-1}$. Far from the black hole $r > 1000r_{\text{g}}$, where $r_{\text{g}} = 2GM/c^2$ is the Schwarzschild radius, accreting gas keeps presupernova composition, or that of the O-rich layer, because of low temperatures ($T < 2 \times 10^9 \text{ K}$). As the material falls down, the gas becomes rich in iron-group elements via explosive O-burning, followed by Si-burning. The processed

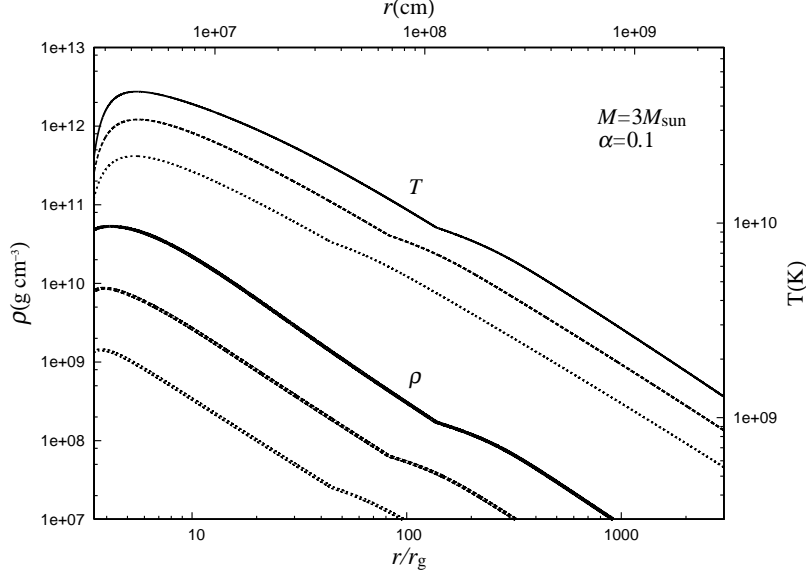


Figure 1. Density and temperature profiles inside the disk with 0.01, 0.1 and $1 M_{\odot} \text{ s}^{-1}$.

heavy elements, however, are destroyed to helium, and finally to protons and neutrons through photodisintegrations deep inside the disk. Near the inner edge of the disk, neutrons are the most abundant by electron captures on protons. Considerable amounts of D, T and ${}^6\text{Li}$ exist due to NSE.

For higher accretion rates, the density is higher, the electron capture is more efficient, and consequently the disk becomes more neutron-rich. In fact, the ratios of neutron to proton are 1.33, 3.50 and 10.4 for $\dot{M} = 0.01$, 0.1 and $1 M_{\odot} \text{ s}^{-1}$, respectively, near the inner edge of the disk. Radial profiles of the electron fraction are similar to those in the other authors.⁸

The disk consists of five layers characterized by dominant elements: ${}^{16}\text{O}$, ${}^{28}\text{Si}$, ${}^{54}\text{Fe}$ (and ${}^{56}\text{Ni}$), ${}^4\text{He}$, and nucleons. Hereafter, these five layers are referred to as the O-rich, Si-rich, Fe-rich, He-rich, and np-rich disk layers. Figure 3 shows the interfaces of these layers for $\dot{M} = 0.01 - 1 M_{\odot} \text{ s}^{-1}$. Temperatures increase with the increasing accretion rate at a given radius, so that the individual layers shift outward, but the overall profiles of composition are preserved. This is because nucleosynthesis inside a disk mainly depends on the temperature distribution of the disk. Averaged mass fractions over the individual layers of 40 abundant nuclei are given in Table 1 for the Fe-rich and He-rich disk layers with $\dot{M} = 0.01$ and $0.1 M_{\odot} \text{ s}^{-1}$. We find that the averaged abundances of the individual disk layers are not

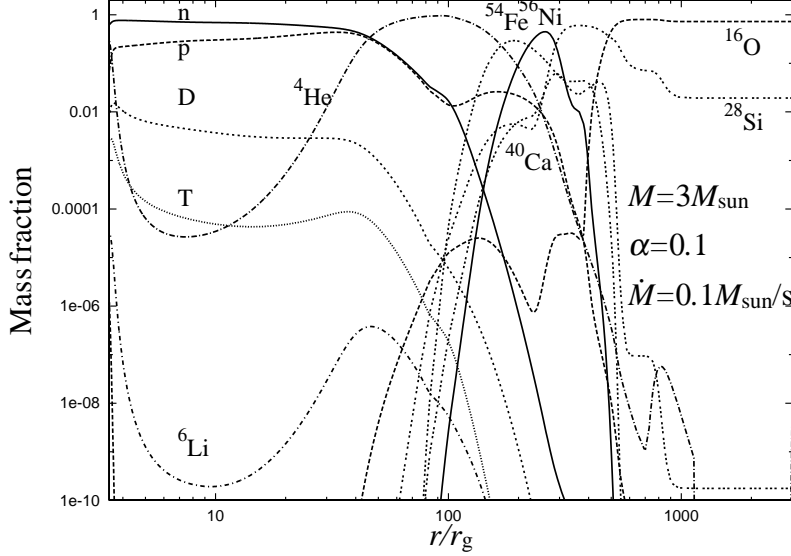


Figure 2. Abundance profiles of representative nuclei inside the disk with $0.1M_{\odot} \text{ s}^{-1}$.

significantly changed as the accretion rates.

4. Chemical Composition of Disk Winds

4.1. ^{56}Ni in Winds

During accretion onto a black hole, some fractions of accreting gas could be ejected through winds from an accretion disk. Possible processes driving the wind are magnetical centrifugal force¹⁵ and viscosity.³ Abundances of ejecta through the wind change via decay processes as well as charged particle and capture processes because of high densities and temperatures of the ejecta. The abundances hence depend not only on initial conditions of the ejecta (abundances, density, temperature, and so on) but also on hydrodynamics of the wind. Detailed dynamics of the wind is, however, still uncertain. We therefore adopt a simple hydrodynamical model of the wind,¹⁶ where the gasses are assumed to be adiabatic and freely expanding. The ejection velocity v_{ej} is set to be $10^{-4} - 0.1v_{\text{K}}$ with the Keplerian velocity v_{K} at the ejection radius r_{ej} of the disk. The density and temperature of the wind are initially taken to be those of the disk at r_{ej} . We note that the entropy per baryon are 10–20 in units of the Boltzmann constant and that the non-relativistic entropies are always larger than the relativistic ones in

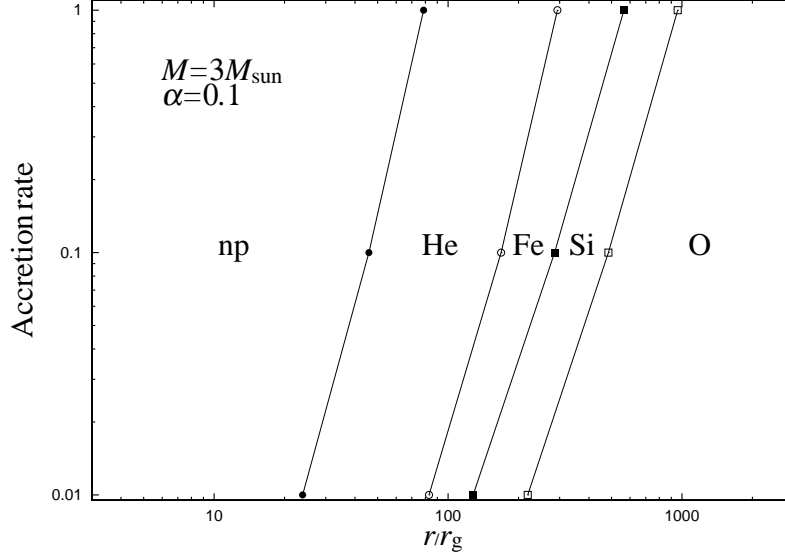


Figure 3. Interfaces of various layers. The disk consists of five layers characterized by dominant elements: ^{16}O , ^{28}Si , ^{54}Fe (and ^{56}Ni), ^4He , and nucleons.

the ejecta. The adiabatic index is accordingly taken to be $5/3$.

Using density and temperature evolution calculated with the above wind model, we can evaluate change in abundances of the ejecta from an initial composition which is the same as in the accretion disk at r_{ej} , with similar post-processing calculations to those in accretion disks. We have calculated abundance change through wind launched from the inner region ($r_{\text{ej}} \leq 200r_g$) of the disk with $\dot{M} = 10^{-4} - 0.1M_{\odot} \text{ s}^{-1}$. In briefly, the abundances through the winds ejected from the O-rich and Si-rich disk layers are found to be not largely changed from those of the disk. On the other hand, for the winds from the He-rich and np-rich disk layers, the composition is largely altered from that of the disk.

In Figure 4, we show the mass fractions of ^{56}Ni inside the winds from the accretion disk with $\dot{M} = 0.01M_{\odot} \text{ s}^{-1}$. The abscissa is the radius from which the wind is launched. The abundances are evaluated at the time when $T_{\text{ej}} \simeq 5 \times 10^8 \text{ K}$. Abundant radioactives have not decayed significantly until the epoch. We find that the winds from the np-rich disk layer are abundant in ^{56}Ni , as suggested by the several authors.^{3,8} We also find that ^{56}Ni is the most abundant in the ejecta from not only the np-rich layer but also the He-rich and Fe-rich layers and inner parts of the Si-rich layer. The smallness

Table 1. Averaged abundances in the Fe and He layer of the disk before decay.

Fe-rich disk layer				He-rich disk layer			
0.01 $M_{\odot} \text{ s}^{-1}$		0.1 $M_{\odot} \text{ s}^{-1}$		0.01 $M_{\odot} \text{ s}^{-1}$		0.1 $M_{\odot} \text{ s}^{-1}$	
elem.	X	elem.	X	elem.	X	elem.	X
Fe54	2.47E-01	Ni56	2.59E-01	He4	6.68E-01	He4	6.29E-01
Ni56	1.67E-01	Fe54	1.82E-01	Fe54	5.12E-02	Fe54	5.49E-02
Co55	1.13E-01	Co55	1.17E-01	p	4.34E-02	p	4.08E-02
Ni58	7.22E-02	Ni58	6.10E-02	Fe56	3.58E-02	Fe56	3.60E-02
He4	6.77E-02	Ni57	5.12E-02	n	3.18E-02	n	3.04E-02
Ni57	4.58E-02	Si28	4.68E-02	Fe55	2.68E-02	Fe55	3.02E-02
Si28	4.28E-02	He4	4.58E-02	Mn53	1.88E-02	Mn53	2.13E-02
S32	3.88E-02	S32	4.18E-02	Co57	1.40E-02	Co57	1.62E-02
Fe52	2.41E-02	Fe52	3.26E-02	Cr52	1.37E-02	Cr52	1.49E-02
Fe53	2.19E-02	Fe53	2.22E-02	Ni58	1.27E-02	Ni58	1.45E-02
Ca40	1.95E-02	Ca40	2.12E-02	Mn54	1.07E-02	Mn54	1.41E-02
Fe55	1.79E-02	Ar36	1.82E-02	Cr50	6.81E-03	Cr50	8.35E-03
p	1.75E-02	Co56	1.47E-02	Co56	5.92E-03	Co56	7.81E-03
Ar36	1.72E-02	p	1.33E-02	Co55	5.62E-03	Co55	7.31E-03
Co56	1.64E-02	Fe55	1.31E-02	Ni59	5.56E-03	Ni59	6.94E-03
Cr50	1.38E-02	Cr50	1.03E-02	Ni60	4.92E-03	Cr51	5.57E-03
Co57	1.08E-02	Mn51	9.36E-03	Cr51	4.27E-03	Ni60	5.50E-03
Mn51	9.54E-03	Co57	8.30E-03	Fe57	4.18E-03	Mn55	5.28E-03
Mn53	9.46E-03	Mn53	6.85E-03	Mn55	4.16E-03	Fe57	5.22E-03
Fe56	5.96E-03	Fe56	3.84E-03	Co58	2.99E-03	Co58	4.05E-03
Ni59	4.48E-03	Ni59	3.74E-03	Mn52	2.62E-03	Mn52	3.85E-03
Mn52	3.65E-03	Mn52	3.29E-03	Ni57	2.33E-03	Ni57	3.20E-03
Cr48	2.49E-03	Cr48	3.07E-03	Cr53	2.22E-03	Fe53	2.92E-03
Cr49	2.05E-03	Cr49	1.99E-03	Fe53	1.98E-03	Cr53	2.89E-03
Cr51	1.20E-03	Cr51	9.56E-04	V49	1.35E-03	V49	2.04E-03
Ni60	1.12E-03	V47	8.37E-04	V51	1.32E-03	Mn51	1.88E-03
Cr52	1.03E-03	Ni60	8.04E-04	Co59	1.32E-03	V51	1.74E-03
V47	8.03E-04	Cu59	7.94E-04	Fe58	1.29E-03	Co59	1.73E-03
Cu59	6.08E-04	Cr52	6.81E-04	Mn51	1.21E-03	Fe58	1.70E-03
Mn54	6.08E-04	Co54	5.66E-04	Si28	1.04E-03	Si28	1.38E-03
K39	3.85E-04	Mn54	5.03E-04	Ni56	9.70E-04	Ni56	1.35E-03
Co54	3.81E-04	Ti44	3.80E-04	Cr54	9.19E-04	V50	1.28E-03
Ti46	3.51E-04	Cu60	3.71E-04	V50	7.93E-04	Cr54	1.22E-03
Ti44	3.45E-04	K39	2.92E-04	S32	7.85E-04	S32	1.04E-03
Cu60	3.11E-04	Ti46	2.81E-04	Ni61	7.63E-04	Ni61	1.03E-03
Co58	3.03E-04	Co58	2.61E-04	Ti48	6.17E-04	V48	9.49E-04
V48	2.43E-04	V48	2.59E-04	Mn56	5.64E-04	Mn56	9.44E-04
Cl35	2.14E-04	V49	1.75E-04	V48	5.11E-04	Ti48	8.85E-04
V49	1.95E-04	Ti45	1.59E-04	Ti46	4.36E-04	Cr49	6.41E-04
Cu61	1.51E-04	Cl35	1.56E-04	Cr49	3.88E-04	Ti46	6.29E-04

of ^{56}Ni in the ejecta from $10r_g$ is attributed to efficient neutron capture on iron peak elements. The electron fraction, Y_e , is initially 0.4830 in the ejecta. ^{56}Ni is consequently largely depleted through neutron capture,

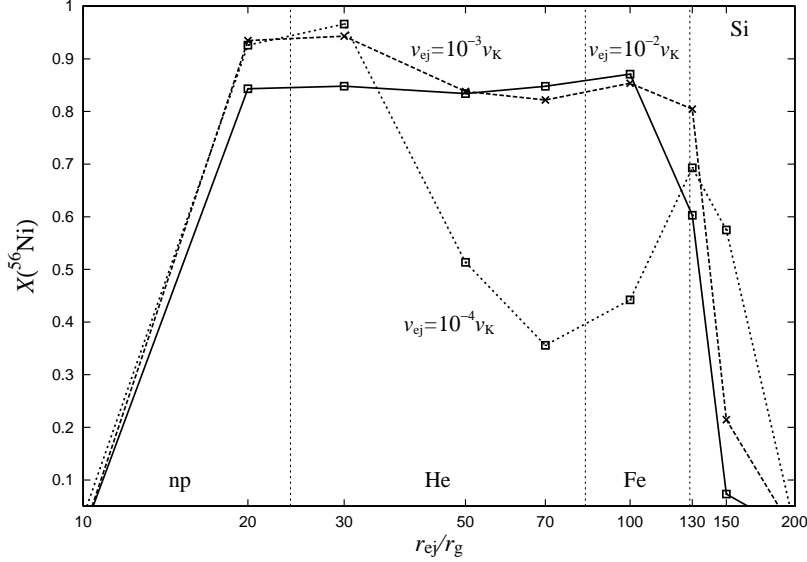


Figure 4. Mass fraction of ^{56}Ni of winds ejected from various disk radii and various ejection velocities.

while more neutron rich nuclei, such as ^{58}Ni , ^{60}Ni , and ^{64}Zn , are abundantly synthesized. On the other hand, in the ejecta launched from $20r_g$ (Y_e is 0.4994 initially), neutron capture on iron peak elements is less efficient in the ejecta. The mass fraction of neutrons in the ejecta from $10r_g$ is larger than that of protons by 0.034, which is too small to conduct r-process successfully.

4.2. Chemical Composition of Winds

We average abundances in winds ejected from the inner region ($r \leq 50r_g$) of the disk to estimate the yields through the winds from the disk. The averaging procedure is the same as in our previous study¹³ but included with a weight of $1 - \exp(-r_{\text{ej}}/50r_g)$, (or 0, whichever is smaller than 0), which means more massive ejection from smaller disk radius less than $50r_g$. Figure 5 shows the yields via the winds from the disk with $\dot{M} = 0.001$, 0.01, and $0.05M_\odot \text{ s}^{-1}$. The total mass of ejecta is set to be $1M_\odot$.³ The profiles of yields are similar for different \dot{M} , but the ejected masses heavier than Cu are larger for higher \dot{M} . This is due to the neutron richness of inner regions of the disk. It should be noted that appreciable amounts of ^{63}Cu and ^{64}Zn can be produced through the winds from the disk without

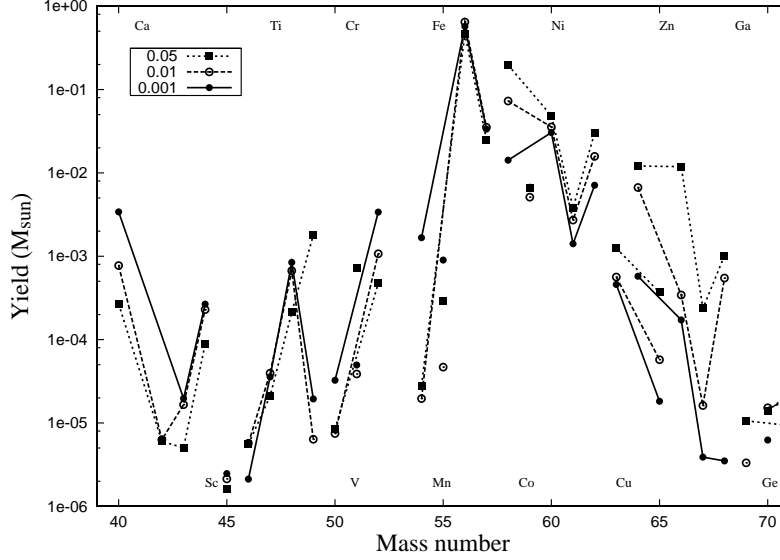


Figure 5. Yields through the wind ejected from the disk with 0.001 (filled circles with solid line), 0.01 (circles with dashed line), and $0.05 M_{\odot} \text{ s}^{-1}$ (squares with dotted line) after decay when the total mass through the wind is $1 M_{\odot}$.

neutron-rich regions (for $0.001 M_{\odot} \text{ s}^{-1}$).

4.3. Chemical Composition of Winds from Neutron-rich Regions of Disks

We investigate abundances in winds from neutron-rich regions of the disk with $\dot{M} \geq 0.1 M_{\odot} \text{ s}^{-1}$. We use the same procedure as in §4.1 but with the larger nuclear reaction network which includes various neutron-rich nuclei. Figure 6 shows the abundances in the wind after decays for the representative case: the wind launched from $r_{\text{ej}} = 10 r_{\text{g}}$ of the accretion disk with $\dot{M} = 0.1 M_{\odot} \text{ s}^{-1}$. The electron fraction and the entropy per baryon are initially 0.30 and $13.1 k_{\text{B}}$, respectively. The ejection velocities of the wind are taken to be $0.01 v_{\text{K}}$ (solid line) and $0.001 v_{\text{K}}$ (dotted line). We find that neutron-rich nuclei are abundantly synthesized in the winds. More massive nuclei can be produced in the slower wind. This is because slower winds have enough time for nuclei to capture neutrons. Nuclei with mass numbers $\simeq 120$ and 180 are abundant for cases with $v_{\text{ej}} = 0.01 v_{\text{K}}$ and $0.001 v_{\text{K}}$, respectively. For faster winds than $0.1 v_{\text{K}}$, on the other hand, light elements are dominant. The abundances in the winds from neutron-rich regions of

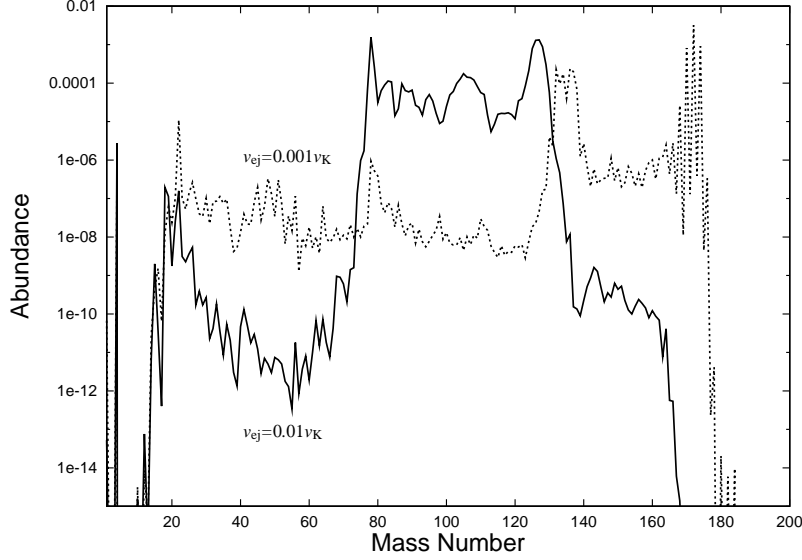


Figure 6. Abundances in the wind ejected from $r_{\text{ej}} = 10r_g$ of the disk with $\dot{M} = 0.1M_{\odot} \text{ s}^{-1}$. The ejection velocities of the wind are taken to be $0.01v_K$ (solid line) and $0.001v_K$ (dotted line).

the disk are sensitive to the ejection velocity as well as the electron fraction. Although the electron fractions are comparable to or less than that of the disk in our wind model, the fractions may increase to be larger than 0.5 if the wind is driven via viscosity.¹⁷ The abundances are likely to strongly depend on hydrodynamics of the wind. The yields from the neutron-rich disk therefore are still uncertain.

5. Summary

We have investigated nucleosynthesis inside the accretion disk associated with GRBs and inside winds launched from an inner region of the disk using the one-dimensional disk and wind models and the nuclear reaction network. The initial composition of accreting gas is taken to be that of an O-rich layer of a $20 M_{\odot}$ star before the core collapse. We have found that the disk consists of five layers characterized by dominant elements: ^{16}O , ^{28}Si , ^{54}Fe (and ^{56}Ni), ^4He , and nucleons, and the individual layers shift inward with keeping the overall profiles of compositions as the accretion rate decreases. ^{56}Ni are abundantly ejected through the wind from the Fe-rich, He-rich and nucleon-rich disk layers with the electron fraction $\simeq 0.5$.

In addition to iron group elements, heavier elements than Cu, in particular ^{63}Cu and ^{64}Zn , are massively produced via the wind. Various neutron-rich nuclei can be produced through the wind from neutron-rich regions of the disk in our simple wind model, though the estimated yields have large uncertainties.

References

1. T. Galama et al., *Nature* **395**, 670 (1998).
2. J. Hjorth et al., *Nature* **423**, 847 (2003).
3. A. I. MacFadyen and S. E. Woosley, *Astrophys. J.* **524**, 262 (1999).
4. A. I. MacFadyen, S. E. Woosley and A. Heger, *Astrophys. J.* **550**, 410 (2001).
5. S. E. Woosley and T. A. Weaver, *Astrophys. J. S.* **101**, 181 (1995).
6. S. Mineshige, H. Nomura, M. Hirose, K. Nomoto and T. Suzuki, *Astrophys. J.* **489**, 227 (1997).
7. S. Nagataki, A. Mizuta, S. Yamada, H. Takabe and K. Sato, *Astrophys. J.* **596**, 401 (2003).
8. J. Pruet, S. E. Woosley and R. D. Hoffman, *Astrophys. J.* **586**, 1254 (2003).
9. T. Di Matteo, R. Perna and R. Narayan, *Astrophys. J.* **579**, 706 (2002).
10. K. Kohri and S. Mineshige, *Astrophys. J.* **577**, 311 (2002).
11. M. Hashimoto, *Prog. Theor. Phys.* **94**, 663 (1995).
12. S. Fujimoto, K. Arai, R. Matsuba, M. Hashimoto, O. Koike and S. Mineshige, *Publ. Astron. Soc. Japan* **53**, 509 (2001).
13. S. Fujimoto, M. Hashimoto, O. Koike, K. Arai and R. Matsuba, *Astrophys. J.* **585**, 418 (2003).
14. D. D. Clayton, 1968, *Principles of Stellar Evolution and Nucleosynthesis* (New York: MacGraw-Hill)
15. F. Daigne and R. Mochkovitch, *Astron. Astrophys.* **388**, 189 (2002).
16. C. Freiburghaus et al., *Astrophys. J.* **516**, 381 (1999).
17. J. Pruet, T. A. Thompson and R. D. Hoffman, *Astrophys. J.* appeared (2004) (astro-ph/0309278).